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Dynamic contribution analysis of badminton-smash-motion with consideration of racket shaft deformation (A model consisted of racket-side upper limb and a racket)

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Abstract

The purpose of this study was to develop a methodology that quantifies the contributions of the racket-side upper limb joint torques and shaft restoring torque to the generation of racket head speed during the badminton smash motion. The racket-side upper limb was modelled as successive rigid segments, such as upper arm, forearm and hand segments. The racket shaft was divided into a set of rigid segments connecting to its adjacent segments via virtual joints with rotational spring. The contributions of the joint torque term, motion-dependent term, gravitational term, and shaft restoring torque term to the generation of racket head speed were calculated from the equation of motion for the system consisting of racket-side upper limb and racket. A new algorithm which converts motion dependent term into other terms was proposed to investigate the main factor of the motion dependent term. The results showed that 1) the motion dependent term was the largest contributor to the generation of head speed prior to the impact, and 2) the shaft restoring torque term was positive contributor to the generation of motion dependent term over the forward swing period in the badminton smash motion.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

Keywords: Badminton Smash; Shaft Deformation; Dynamics Analysis; Dynamic Contribution

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1. Introduction

The badminton smash is one of the highest tip-speed motions among various sports hitting motions. In the baseball pitching motion, which is considered as high speed swing motion, previous studies indicate that the motion dependent term, e.g. sum of centrifugal force, Coriolis force, and gyro moment terms (hereafter referred to as MDT), plays a significant role for the generation of end-point speed of linked segment systems (Naito et al., 2008; Hirashima et al., 2008). Although the badminton smash is a high-speed swing motion, the speed generation mechanism has not been examined. Additionally, racket shaft has elasticity due to its material property. However, the effect of the elastic characteristics on the tip-speed generation mechanisms of the swing motion has not been clarified. The purpose of this study was to develop a methodology that quantifies the contributions of the racket-side upper joint torques and shaft restoring torque to the generation of racket head speed during the badminton smash motion.

Nomenclature

$\boldsymbol{V}$	generalized velocity vector consisted of translational and rotational velocity vectors of all segments
$\boldsymbol{F}$	force vector composed of joint force vectors
$\boldsymbol{F}_{\mathrm{ext}}$	external force vector exerting on racket-side shoulder joint
$\boldsymbol{N}$	moment vector composed of each joint moment
$\boldsymbol{T}_{\mathrm{act}}$	active joint torque vector composed of individual joint axial torques

2. Methods

2.1. Modelling of racket-side upper limb and racket system

The racket-side upper limb was modelled as linked 3 rigid segments (upper arm, forearm and hand) that have 7 DOFs (3 for shoulder, 2 for elbow and 2 for wrist) considering anatomical constraint degrees of freedom at joint axes, e.g. inversion/eversion axis of the elbow joint, and internal/external rotation of the wrist joint (Fig.1). The racket model consisted of grip handle, racket shaft and face. The racket shaft was divided into a set of rigid segments connecting to its adjacent segments via virtual joints (Fig.1). The grip handle segment was connected to the hand segment via a virtual joint with 0 DOF.

2.2. Equation of motion for the system

The translational and rotational equations of motion for each segment of system can be summed up in a matrix form as follows:

$$\boldsymbol{M}\dot{\boldsymbol{V}} = \boldsymbol{P}\boldsymbol{F} + \boldsymbol{P}_{\mathrm{ext}}\boldsymbol{F}_{\mathrm{ext}} + \boldsymbol{Q}\boldsymbol{N} + \boldsymbol{H} + \boldsymbol{G} \tag{1}$$

where $\boldsymbol{M}$ is the inertia matrix and $\boldsymbol{V}$ is the vector containing the translational and rotational velocity vectors of each segment's CG, $\boldsymbol{P}$ and $\boldsymbol{P}_{\mathrm{ext}}$ are the coefficient matrices of vector $\boldsymbol{F}$ which contains all joint force vectors and of external force vector $\boldsymbol{F}_{\mathrm{ext}}$, $\boldsymbol{Q}$ is the coefficient matrix of vector $\boldsymbol{N}$ which contains moment vectors at all joints, $\boldsymbol{H}$ is the vector containing gyro moment vectors of all segments, and $\boldsymbol{G}$ is the vector of the gravitational component.

The equation for constraint condition in which adjacent segments are connected by joint is expressed as follows:

$$\boldsymbol{C}\boldsymbol{V} = \boldsymbol{0} \tag{2}$$

where $\boldsymbol{C}$ is the geometric constraint coefficient matrix of the generalized velocity vector.

The geometric equations for constraint axes of joints, such as, inversion/eversion axis of the elbow and internal/external rotation of the wrist joint can be expressed in matrix form as follows:

$$\boldsymbol{A}\boldsymbol{V} = \boldsymbol{0} \tag{3}$$

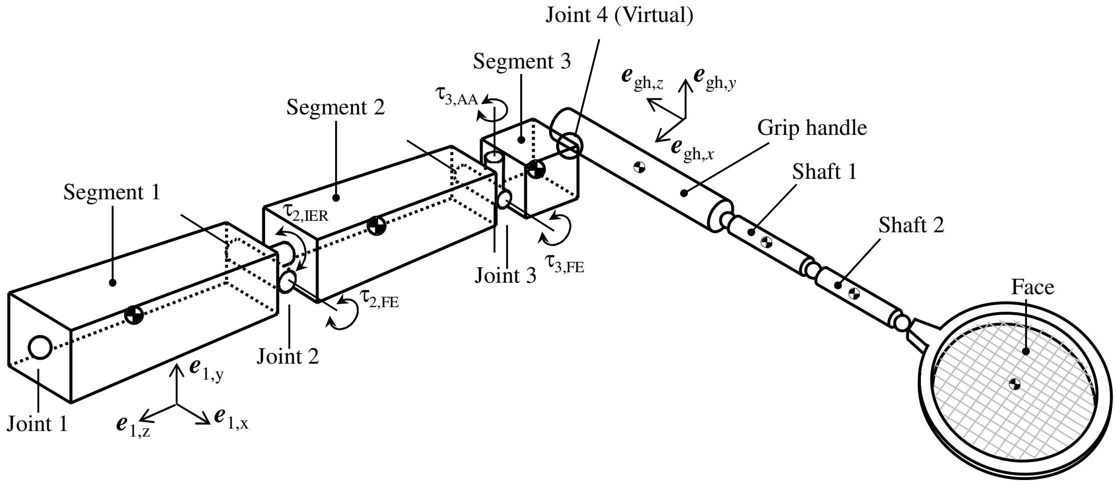


Fig.1. A schematic representation of linked-segment model of the racket-side upper limb and badminton racket

where $\boldsymbol{A}$ is the anatomical constraint coefficient matrix of the generalised velocity vector.

Substituting equations (2) and (3) after differentiating with respect to time into equation (1), the equation of motion for the system can be obtained, which is written by the following matrix form expression as follows:

$$\dot{\boldsymbol{V}} = \boldsymbol{A}_{\boldsymbol{F}\mathrm{e}}\boldsymbol{F}_{\mathrm{ext}} + \boldsymbol{A}_{\boldsymbol{Ta}}\boldsymbol{T}_{\mathrm{act}} + \bar{\boldsymbol{A}}_{v}\boldsymbol{V} + \boldsymbol{A}_{\boldsymbol{G}}\boldsymbol{G} \tag{4}$$

where $\boldsymbol{A}_{\boldsymbol{Fe}}$, $\boldsymbol{A}_{\boldsymbol{Ta}}$, and $\boldsymbol{A}_{\boldsymbol{G}}$ are the coefficient matrices of the external force vector $\boldsymbol{F}_{\mathrm{ext}}$, the active joint torque vector $\boldsymbol{T}_{\mathrm{act}}$, and the gravitational acceleration vector $\boldsymbol{G}$, and $\bar{\boldsymbol{A}}_{v}\,\boldsymbol{V}$ denotes the motion dependent term.

Integrating equation (4) with respect to time, one can obtain dynamic equation relating the generalized velocity vector to the terms such as external force, active joint torques, motion dependent and gravitational terms. Furthermore, by extracting evaluation variables using a selecting matrix, one can quantify contribution of the terms to the generation of target variables.

2.3. Modelling of elastic characteristics of racket shaft

The elastic characteristics of the racket shaft were represented by using the restoring torques exerted about the individual virtual joints. The restoring torques were calculated as the product of the angular displacements of divided shaft segments and the stiffness of the rotational spring settled at the virtual joints. The joint torque term in equation (6) can be divided into the human active joint torque term and the racket shaft restoring torque term as follows:

$$\boldsymbol{A}_{\boldsymbol{Ta}}\boldsymbol{T}_{\mathrm{act}} = \boldsymbol{A}_{\boldsymbol{TH}}\boldsymbol{T}_{\boldsymbol{H}} + \boldsymbol{A}_{\boldsymbol{TS}}\boldsymbol{T}_{\boldsymbol{S}} \tag{5}$$

where $\boldsymbol{A}_{TH}$ and $\boldsymbol{A}_{TS}$ are the coefficient matrices of the active joint torque vector $\boldsymbol{T}_{\mathrm{H}}$ and of the shaft restoring torque vector $\boldsymbol{T}_{\mathrm{S}}$.

The shaft restoring torques can be expressed as follows:

$$\boldsymbol{T}_{\boldsymbol{S}} = \boldsymbol{K}_{\boldsymbol{S}}\boldsymbol{X} \tag{6}$$

where $\boldsymbol{K}_{\mathrm{S}}$ is the coefficient matrix including stiffness matrix for shaft joints, and $\boldsymbol{X}$ is the vector calculated by integration of the generalized velocity vector $\boldsymbol{V}$.

Substituting equations (5) and (6) into equation (4) yields the equation of motion for the racket-human system expressed as follows:

$$\dot{\boldsymbol{V}} = \boldsymbol{A_{TH}}\boldsymbol{T_H} + \boldsymbol{A_{TS}}\boldsymbol{K_S}\boldsymbol{X} + \bar{\boldsymbol{A}}_v\boldsymbol{V} + \boldsymbol{A_G}\boldsymbol{G} + \boldsymbol{A_{Fe}}\boldsymbol{F}_{\mathrm{ext}} \tag{7}$$

where $\boldsymbol{A_{TH}}\boldsymbol{T_H}$ represents the accelerations of individual segments caused by joint torques, the second term, $\boldsymbol{A_{TS}}\boldsymbol{K_S}\boldsymbol{X}$ represents the accelerations caused by shaft deformation, $\bar{\boldsymbol{A}}_v\boldsymbol{V}$ represents the accelerations caused by the motion-dependent torques, e.g. centrifugal force, Coriolis force, and gyro moment, $\boldsymbol{A_G}\boldsymbol{G}$ represents the accelerations caused by gravity, and $\boldsymbol{A_{Fe}}\boldsymbol{F}_{\mathrm{ext}}$ represents the accelerations caused by shoulder joint forces. By integrating equation (7) with respect to time and by extracting racket face velocity from the generalized velocity vector $\boldsymbol{V}$, one can obtain the contribution of individual terms to the generation of the racket head speed $v_{\mathrm{spd,fc}}$ as follows:

$$v_{\mathrm{spd,fc}} = \boldsymbol{e}_{v\mathrm{fc}}^{\mathrm{T}}\boldsymbol{S}\int \boldsymbol{A_{TH}}\boldsymbol{T_H}dt + \boldsymbol{e}_{v\mathrm{fc}}^{\mathrm{T}}\boldsymbol{S}\int \boldsymbol{A_{TS}}\boldsymbol{K_S}\boldsymbol{X}dt + \boldsymbol{e}_{v\mathrm{fc}}^{\mathrm{T}}\boldsymbol{S}\int \bar{\boldsymbol{A}}_v\boldsymbol{V}dt + \boldsymbol{e}_{v\mathrm{fc}}^{\mathrm{T}}\boldsymbol{S}\int \boldsymbol{A_G}\boldsymbol{G}dt + \boldsymbol{e}_{v\mathrm{fc}}^{\mathrm{T}}\boldsymbol{S}\int \boldsymbol{A_{Fe}}\boldsymbol{F}_{\mathrm{ext}}dt \tag{8}$$

where $\boldsymbol{S}$ denotes a selective matrix, and $\boldsymbol{e}_{v,\mathrm{fc}}$ is the unit vector of racket head velocity vector. The five terms on the right side of equation (8) represent the active joint torque term, shaft restoring torque term, motion dependent term, gravitational term, and external force term.

2.4. Modelling of racket shaft deformation

The shaft deformation was described as the angular displacement at individual virtual joints. The deformation curve of racket shaft was approximated by using a 2nd order polynomial function fitted from measured coordinate data obtained under the smash and drive shot conditions in order to calculate the angular displacements of each virtual joint. The coordinate data were captured with a motion capture system (VICON-MX, VICON Motion Systems Inc.). Marker position data were recorded at 500Hz. The translational velocity of each shaft segment's centre of gravity (CG) and the angular velocity of each segment were calculated by using the approximate function.

2.5. Converting algorithm of motion dependent term into other terms

The previous studies regarding to the speed generation mechanism in the baseball pitching motion have shown that the motion dependent term play a crucial role to generate the hand speed prior to the ball release. Since the racket head is accelerated to about 50 m·s^{-1} before the impact in order to obtain large shuttlecock speed in the badminton smash motion, the motion dependent term must be a great contributor to the generation of racket head speed in the smash motion. Therefore, we convert it into the terms such as active joint torque term, shaft restoring torque term, gravitational term and external force term.

The equation of motion for system was discretized as follows:

$$\dot{\boldsymbol{V}}(k) = \boldsymbol{\Lambda}_V(k) + \bar{\boldsymbol{A}}_V(k)\boldsymbol{V}(k) \tag{9a}$$

$$\boldsymbol{\Lambda}_V = \boldsymbol{A_{Fe}}\boldsymbol{F}_{\mathrm{ext}} + \boldsymbol{A_{TH}}\boldsymbol{T_H} + \boldsymbol{A_{TS}}\boldsymbol{T_S} + \boldsymbol{A_G}\boldsymbol{G} \tag{9b}$$

The generalised acceleration vector was expressed by difference approximation shown as

$$\dot{\boldsymbol{V}}(k) = \frac{\boldsymbol{V}(k+1) - \boldsymbol{V}(k)}{\Delta t} \tag{10}$$

Combining equations (9a) and (10) yields a recurrence formula for the generalised velocity vector $\boldsymbol{V}$ as follows:

$$\boldsymbol{V}(k+1) = \Delta t\boldsymbol{\Lambda}_V(k) + \boldsymbol{\Psi}_V(k)\boldsymbol{V}(k), \quad \boldsymbol{\Psi}_V(k) = \boldsymbol{E} + \Delta t\bar{\boldsymbol{A}}_V(k) \tag{11}$$

Equations (9b) and (11) provide us the information about the contribution of input terms (e.g., individual axial torques at racket-side upper limb joints, external force exerted on the racket-side shoulder joint, and shaft restoring torque) except MDT to the generation of speed of racket face segment.

3. Experiment

Eleven collegiate badminton players (height: 1.75 ± 0.07 m, weight: 65.3 ± 5.2 kg) participated in the experiment as subjects. The informed consent was obtained from each subject. They performed badminton smash shots by hitting shuttlecocks which were thrown from the other side of the court. The motions were captured with a motion capture system (VICON-MX, VICON Motion Systems Inc.). Marker position data were recorded at 500Hz. The forward swing motion was analysed from the time when the racket head-top speed was minimum value to the time of impact (Fig.2).

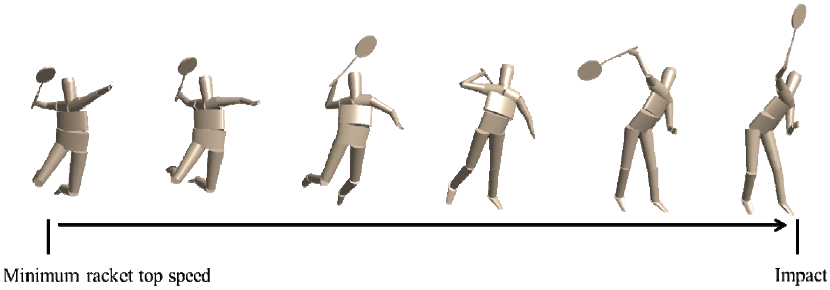
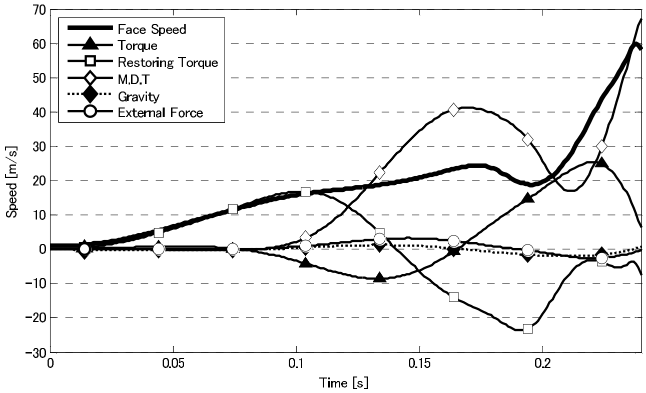
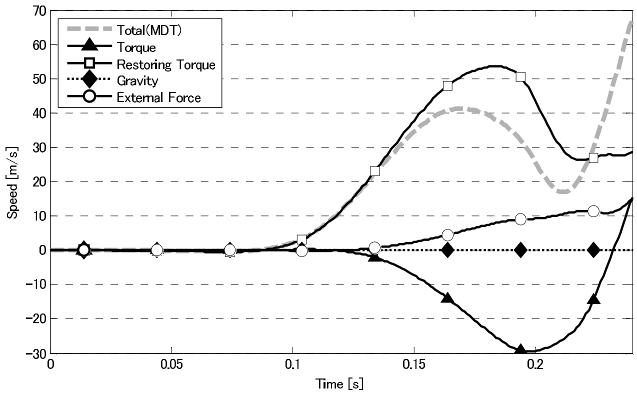


Fig.2. Picture of smash motion



(a). Contribution of the terms to the racket head speed



(b). Contribution to the MDT

Fig.3. Racket face speed generating mechanism in the badminton smash motion

4. Results

An example of contribution of each term to the generation of racket head speed is shown in Figure 3(a). The contribution of motion dependent term increased exponentially right before the impact. The shaft restoring torque contributed to the racket face speed positively in the first half and negatively in the latter half of the forward swing motion. The contribution of active joint torques increased from 0.14 s to 0.23 s in the forward swing motion. The contribution of shoulder joint forces increased positively from 0.1 s to 0.15 s and decreased from 0.15 s to 0.25 s. In addition, the contribution of joint torques was larger than joint forces significantly at the impact.

The contributions to the motion dependent term in Figure 3(a) are shown in Figure 3(b). The contribution of shaft restoring torques to generation of the motion dependent term increased from 0.1 s to 0.18 s and decreased till 0.23 s in the forward swing motion. The contribution of active joint torques decreased from 0.13 s to 0.18 s and then increased to the impact. The external force term contributed positively from 0.13 s to the impact.

5. Discussion

The results showed that the motion dependent term, the shaft restoring torque term and joint torque terms are large positive or negative contributors to the generation of racket head speed during the forward swing phase. The contributions of joint torque term and shaft restoring torque term tended to show opposite sign value. After converting the motion dependent term into other terms, the results indicate that the motion dependent term is mainly caused by shaft restoring torque term and cancelled by negative contribution of joint torque term around 0.05 s before the impact. Since the deformation of racket shaft is caused by the joint torques, a new algorithm which converts the shaft restoring torque term into the joint torque term should be required to investigate head speed generating mechanism.

6. Conclusion

We have developed a method of quantifying the contribution of the racket-side upper limb joint torques and shaft restoring torque on the head speed generation mechanism during the badminton smash motion. The results showed that 1) the motion dependent term was the largest contributor to the generation of head speed right before the impact, and 2) the shaft restoring torque term was positive contributor to the generation of motion dependent term over the forward swing period in the badminton smash motion. Although this study focused on analysis of badminton smash motion, this method can be used to analyse other types of badminton swing motions, such as drive and high clear shots. Additionally, this method can be readily applied to the analyses of other hitting motion using a hitting tool that has flexible elements such as a golf club.

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